Reading notes (outdated)
MSc Ocean Physics, University of Victoria

Kurtis Anstey

April 22, 2021

1 Reading notes

INCOMPLETE

A selection of papers that are useful, or at least informative:

Gemmrich, J., & Klymak, J. M. (2015). Dissipation of internal wave energy generated on a critical slope. *Journal of Physical Oceanography* , *45* (9), 2221–2238. https://doi.org/10.1175/JPO-D-14-0236.1

- Summary: Uses models with varying parameters to attempt to better understand internal waves and tides interacting over 'critically' sloped topography, and how this affects local energy dissipation and mixing. A 'critical' slope matches the propagation angle of travelling internal waves. Vertical shear during incident upslope currents leads to stratification and a bore-like phenomenon, causing high dissipation rates near the bottom. The dissipation dependence can be likened to an oscillating wedge in a stationary fluid. The entire process can be parameterised by a power law, and is useful for describing the tidal dissipation of internal wave energy near shelf topography.
- Methods: a comparison of real-world data to model results, evaluation of **slope angle** and other topographical features, identification of **local parameters** (f , N, etc.).

Klymak, J. M., Alford, M. H., Pinkel, R., Lien, R. C., Yang, Y. J., & Tang, T. Y. (2011). The breaking and scattering of the internal tide on a continental slope. *Journal of Physical Oceanography* ,*41* (5), 926–945. https://doi.org/10.1175/2010JPO4500.1

- Summary: Barotropic conversion of energy over abrupt topography generates low-mode internal tides that radiate away, carrying incident energy with it, rather than through local dissipation effects. This energy eventually hits significant shelf topography, and depending on whether the slope is sub- or super-critical to the incident internal tides, will be scattered or reflected. This study looks at the internal tide generating Luzon region, and the interaction of resultant internal tides with the nearby continental slope, and finds that the results likely follow a linear model of reflection, as predicted, with about 1/3 incident energy being reflected in the first mode (highly dependent on the phase of incident modes 1 and 2). There is also significant local dissipation, and evidence that shelfs are eroded by incident tides until they reach critical slope. Therefore, dissipation near shelfs is likely, but for supercritical slopes reflection is also significant.
- Methods: estimating **energy budgets** and propagation, identifying areas of critical slope and determining energy of **reflection or scattering** , distinguishing local wave generation from incoming, temporal definitions for local tidal constituents, signal decomposition (remove vertical means, tidal filters), further decomposition into vertical modes, shoreward net energy fluxes, identifying local overturns/dissipation/non-linear shocks

Thomson, R. E., & Krassovski, M. V. (2015). Remote alongshore winds drive variability of the California Undercurrent off the British Columbia-Washington coast. Journal of Geophysical Research: Oceans

- Summary: Variability in the California Undercurrent is defined using ADCP data from the A1 and BP2 sites at a higher vertical resolution than previously possible, and wind-generated coastal-trapped waves are evaluated for their contributions to this variability. Other, previously unnoted currents, are also detailed.
- Methods: Velocity data from ADCP can be used to define seasonal and annual variations in mean currents at various depths, and compared to these findings. In particular, the A1 mooring site is near to Barkley Canyon (25 km), and at a similar depth (500 m), during similar years (Series 2). If similar, perhaps some of these findings can be associated with internal wave generation by currents over the shelf/canyon.
- Methods: Obtain similar wind data from NOAA instruments or NARR near Barkley Canyon, to compare with seasonal variability in currents and internal waves.
- Methods: Emulate filtering and rotation methods for better comparison and proven methodology.
- Methods: Wavelet analysis for coherence between wind/current data between A1 and Barkley Canyon.

- Read: ‘Neptune effect’? Holloway (1992) “Representing topographic stress…”
- Question: Why do wind effects from farther away (down the US coast) affect the Vancouver Island currents more than local wind effects?
- Question: How do coastal-trapped waves play a role in this variability coherence?
- Question: How relevant is the Oceanic Nino Index to internal wave variability, generally?

Mihaly, S. F., Thomson, R. E., & Rabinovich, A. B. (1998). Evidence for nonlinear interaction between internal waves of inertial and semidiurnal frequency. Geophysical Research Letters, 25(8), 1205–1208. https://doi.org/10.1029/98GL00722

- Summary: To better understand large-scale energy decay in the internal wave band, non-linear wave-wave interaction is suggested between the f and M2 frequencies caused by downward inertial wind waves and upward topographic internal tides.
- Methods: Look into the fM2 and M4 frequencies, their relative energy (versus total), and seasonal (winter) intensification. Rotary spectra and spectrograms useful for analysis. Compare to these findings, albeit at a greater depth (2000 m) and distant (250 km).
- Read: D’Asaro (1995) “Upper-ocean inertial currents…”
- Read: Thomson (1990) “Near-inertial motions over…”
- Question: Why does a predominantly CW energy suggest the energy is in the form of a ‘freely’ propagating internal wave? Something to do with Coriolis?

Alford, M. H., Cronin, M. F., & Klymak, J. M. (2012). Annual cycle and depth penetration of wind-generated near-inertial internal waves at ocean station papa in the northeast pacific. Journal of Physical Oceanography

- Summary: Two years of ADCP velocity data were analysed at Ocean Station Papa in the Northeast Pacific, to better understand the role of downward penetrating near-inertial internal waves (>800 m) in mixing the deep ocean, as generated by passing storms at the surface. Some of the analysis is still beyond me, at this point.
- Methods: Compare regional wind data to the downward motion of near-inertial internal wave energy to compare to these findings, as moorings are at similar depths (<800 m) but in deep water and distant (1000 km). Evidence of propagation as downward and rightward swathes in the velocity profiles, following storms.
- Methods: Evaluate pressure to determine data quality of ADCP (depth variability).
- Methods: WKB scaling of buoyancy and velocity data through depth, to obtain proper estimates of energy, and apply GM theory. Energy calculations seem quite involved.
- Question: “Because purely inertial motions do not propagate vertically or horizontally, the frequency difference…” “To propagate, the waves must be somewhat super-inertial…” “Clockwise polarisation with depth indicates downward motion…”

Allen, S. E., Vindeirinho, C., Thomson, R. E., Foreman, M. G. G., & Mackas, D. L. (2001). Physical and biological processes over a submarine canyon during an upwelling event. Canadian Journal of Fisheries and Aquatic Sciences, 58(4), 671–684. https://doi.org/10.1139/f01-008

- Summary: An intense and short sampling of Barkley Canyon in July 1997 shows similarities to the Astoria Canyon off the coast of Washington, where summer periods of strong upwelling form that advect biological constituents, like zooplankton. These intervals of enhanced upwelling occur when the canyon depth mean currents are running towards the southeast in the summer, thanks to strong NW winds.
- Reading: Klinck (1996), Allen (1996), Hickey (1997); upwelling at canyons.
- Methods: A lot of good topographical and geographic information regarding Barkley Canyon in this paper.
- Methods: Can check for the characteristic summer upwelling currents both above and within the canyon, to support these findings, as well as comparative wind data.

- Methods: Buoy 46206 for wind data (seaward of Barkley Sound).
- Questions: This upwelling results in high concentrations of zooplankton above the canyon; could this be the harmonics in the w spectra near the surface?
- Questions: Is the Northeast Pacific Coastal Current the main source of the flow to the NW that is present for much of the year (Thomson)?
- Questions: Are hydrographic lines B and C still operational?
- Questions: What is the 24 sigma-t surface? Something to do with the mixed layer and pycnocline?

Martini, K. I., Alford, M. H., Kunze, E., Kelly, S. M., & Nash, J. D. (2013). Internal bores and breaking internal tides on the Oregon continental slope. In Journal of Physical Oceanography (Vol. 43). https://doi.org/10.1175/JPO-D-12-030.1

- Summary: Martini *et al* propose that non-linear internal bores are responsible for much of the internal tide dissipation on the Oregon continental slope, as they lead to vertical transport due to mixing. They provide evidence that bores have a periodicity of approximately 12h, potential phase locking to baroclinic tides, and increased dissipation rates.
- Reading: Carter (2002) "Intense, variable mixing...", canyons. Kunze (2012), canyons. Thurnherr (2005), canyons.
- Methods: Obtain a cross-section of local bathymetry.
- Methods: Look for evidence of upslope mixing due to internal bores incident on the shelf, by identifying a conversion of barotropic or incoming baroclinic tides to local internal tides, and phase locking with forcing.
- Methods: Identify slope angle and investigate reflection or scattering.
- Questions: Barotropic surface tides are 'depth independent', but is there diminishing effect with depth for generating baroclinic internal tides as the surface tides move water over irregular bathymetry?

Kunze, E., Mackay, C., Mcphee-Shaw, E. E., Morrice, K., Girton, J. B., & Terker, S. R. (2012). Turbulent mixing and exchange with interior waters on sloping boundaries. Journal of Physical Oceanography, 42(6), 910–927. https://doi.org/10.1175/JPO-D-11-075.1

- Summary: Well-stratified turbulent layers are found near the bottoms of submarine canyons, and are of an order of magnitude thicker than the well-mixed bottom boundary layers. This indicates that mixing efficiency above submarine canyons holds in the presence of internal wave generation or interaction with the irregular canyon topography. Furthermore, canyon topography is important to the strength of turbulent mixing, which varies over its structure. Up-canyon turbulence-driven transport occurs, where it contributes to greater mixing effects between the turbulent layer and interior. This all suggests that 1D interpretations of canyon mixing effects are inadequate for physical models.
- Question: Do more research into thermohaline circulation, as briefly discussed in class.
- Question: Do more research into abyssal sub-inertial currents, as one of the main energy sources for mixing in the ocean interior.
- Question: Find a better definition of 'fine-structure' as it applies to oceanography.
- Methods: Identify near-bottom stratified turbulent layers, with ADCP? Seems to be more accurate with CTD, as near-bottom data of ADCP is often compromised.

Carter, G. S., & Gregg, M. C. (2002). Intense, variable mixing near the head of Monterey Submarine Canyon. In Journal of Physical Oceanography (Vol. 32). https://doi.org/10.1175/1520

- Summary: Intense diapycnal mixing is found to occur in the Monterey Submarine Canyon, as compared to the open ocean, due to scattering and reflection of internal wave energy that focuses towards the head of the canyon, contributing to greater energy density and therefore turbulence (such as bores) in this region. This reflects research suggesting that interaction with canyon topography can more efficiently transfer energy to small scales than wave-wave interactions. The structure of the canyon (bottom and wall slopes, bends, width, depth, etc.) contributes to these effects, and different canyon regions experience greater turbulent effects during different periods of the tidal cycle (ranging from

diurnal to spring/neap). As submarine canyons are a notable portion of continental shelves, they are suggested to contribute a small but significant portion of the global internal tide mixing budget.
- Question: What are expendable current profilers (XCP)?
- Methods: Determine wall slope angles to check depth reliability of Axis ADCP data (up to lower 30% of depth unreliable for 'steep' sides).

Kunze, E. (2017). Internal-wave-driven mixing: Global geography and budgets. Journal of Physical Oceanography, 47(6), 1325–1345. https://doi.org/10.1175/JPO-D-16-0141.1

- Summary: Internal wave breaking contributes a significant portion of the global mixing budget (about 2.1 TW). Internal wave-wave interaction is investigated for finescale parameterisation of shear and strain and their contribution to this mixing, determined though a study involving about 30,000 CTD casts, globally. They found that internal wave generation generally increased over abrupt topography due to elevated strain variance, and that most of this mixing occurs in the upper 1000 m. Their estimations indicate that internal waves do indeed drive open and deep ocean mixing processes, as estimated energy budgets align within uncertainty with those expected.
- Question: What's the definition of finescale and/or microstructure?
- Methods: Energy budget identification (perhaps beyond the scope of this research?)
- Reading: J. A. MacKinnon, Z.-X. Zhao, R. Pinkel, J. Klymak, and T. Peacock, 2007: Internal waves across the Pacific. Geophys. Res. Lett., 34, L24601, doi:10.1029/2007GL031566.
- Reading: Alford, M. H., Girton, J. B., Voet, G., Carter, G. S., Mickett, J. B., and Klymak, J. M. (2013). Turbulent mixing and hydraulic control of abyssal water in the Samoan Passage. Geophys. Res. Lett. https://doi.org/10.1002/grl.50684

Robertson, R., Dong, J., & Hartlipp, P. (2017). Diurnal Critical Latitude and the Latitude Dependence of Internal Tides, Internal Waves, and Mixing Based on Barcoo Seamount. Journal of Geophysical Research: Oceans, 122(10), 7838–7866. https://doi.org/10.1002/2016JC012591

- Summary: Critical latitudes are important for tidal frequencies, as they can enhance the effects of prominent (diurnal and semidiurnal) internal tides in those regions. Essentially, diurnal tides are generated and are immediately resonant in these regions, trapping the energy poleward of this latitude and distributing energy into higher frequencies, such as the semi-diurnal tides, etc., consistent with non-linear internal wave-wave interaction theory. Observations indicate that critical latitudes are important to consider in analysis of internal wave/tide generation in a region.
- Question: Why do the internal waves get trapped poleward (this is probably in the paper somewhere, but I must have skimmed over it)?
- Methods: Critical latitude analysis for Barkley Canyon (I am not sure that it is relevant, as no other papers in the region have mentioned it, but I can still check).
- Reading: Jayne, S. R., & St. Laurent, L. C. (2001). Parameterizing tidal dissipation over rough topography. Geophys. Res. Lett., 28(5), 811–814. https://doi.org/10.1029/2000gl012044

Terker, S. R., Girton, J. B., Kunze, E., Klymak, J. M., & Pinkel, R. (2014). Observations of the internal tide on the California continental margin near Monterey Bay. Continental Shelf Research, 82, 60–71. https://doi.org/10.1016/j.csr.2014.01.017

- Summary: Northward bound internal tide energy flux is found to be in abundance off the coast of Monterey Bay, California, due to notable topographical features at Point Sur. Data were obtained using a network of platforms, XCP, and FLIP. Results were found to generally agree with models, though semidiurnal tides were more energetic than expected, and it is thought that smaller spatial scales are necessary to resolve certain internal wave properties in the presence of rough topography.
- Question: What are some significant regions of internal wave/tide generation near the VICS?
- Methods: Ensuring observations are long enough to avoid coastally trapped diurnal waves interfering with semidiurnal tides. This shouldn't be an issue with the ONC data.
- Methods: Identifying energy flux direction for internal tides, to identify where incoming waves are

generated (seems difficult).

- Reading: Rainville, L., Pinkel, R., 2006. Propagation of low-mode internal waves through the ocean. J. Phys. Oceanogr. 36, 1220–1237.

Rainville, L., and Pinkel, R. (2006). Propagation of Low-Mode Internal Waves through the Ocean. Retrieved from http://journals.ametsoc.org/jpo/article-pdf/36/6/1220/4483319/jpo2889_1.pdf

- Summary: To better understand the baroclinic tides and their generation, propagation, and dissipation in the oceans, a model was developed to better account for global processes that would affect internal tides and applied to observations near the Hawaiian Ridge. Their findings help to identify sources of apparent energy loss in internal tides, such as phase modulation and topographic drain. Internal wave/tide propagation speeds are estimated for various modes, and baroclinic 'shoaling' regions are identified to indicate regions of enhanced internal wave activity. Additionally, ray equations are derived and associated with mesoscale currents to create a 'complete' picture of baroclinic propagation. In the end, they determine that a WKB approach to a modal evaluation of internal wave propagation is most effective for realistic results.
- Question: What exactly is phase modulation? I do not understand this concept that well, and it wasn't described in detail.
- Method: A modal analysis of generated waves in the canyon compared to on the plateau could be an interesting comparison.
- Reading: Nash, J., E. Kunze, J. Toole, and R. Schmitt, 2004: Internal tide reflection and turbulent mixing on the continental slope. J. Phys. Oceanogr., 34, 1117–1133.

Nash, J. , Kunze, E., Toole, J. , & Schmitt, R. (2004). Internal Tide Reflection and Turbulent Mixing on the Continental Slope. Retrieved from http://journals.ametsoc.org/jpo/article-pdf/34/5/1117/4470231/1520-0485

- Summary: To better understand the eventual dissipation of low-mode internal tides, observations were made at a steep slope off the coast of Virginia in Spring 1998, where the incoming flux is seemingly reflected back out at higher modes. Various explanations are given for unusually enhanced mixing near the base of the slope, a likely culprit being early reflection of incoming baroclinic tides down to this region. The incoming low-mode energy is though to be from a remote source of M2 internal tide generation that propagates to this slope, where it is reflected and scattered off the near-critical slope as higher-mode waves. These waves travel about 100km before dissipating, and could be an important energy transfer process to drive turbulent mixing in the ocean.
- Question: How do you tell the difference between barotropic and baroclinic tides from velocity data? So far in these papers it's just been stated as obvious. Does it have something to do with a shift in phase, or period?
- Method: Identify incoming barotropic tides to compare with the criticality of the slope near Barkley Canyon, to see if enhanced mixing could occur in this region.
- Reading: Gilbert, D., 1993: A search for evidence of critical internal wave reflection on the continental rise and slope off Nova Scotia. Atmos.–Ocean, 31, 99–122.

Alford, M. H., Mackinnon, J. A., Zhao, Z., Pinkel, R., Klymak, J., Peacock, T., . . . Peacock, T. (2007). Internal waves across the Pacific. Geophys. Res. Lett, 34, 24601. https://doi.org/10.1029/2007GL031566

- Summary: This paper seeks to better understand the propagation of northward internal tides (semidiurnal) from the Hawaiian Ridge, and how they would be affected by parametric subharmonic instability (PSI) at the critical latitude of 28.8 degrees. PSI is a method for generating internal waves through energy extraction from internal tides, and should be detectable as a form of energy loss in the barotropic tides in this region. Though there were energetics associated with PSI detected at this latitude, it was also discovered that the tides propagated further north with less discernible energy loss than was expected. For now, spreading and PSI together can account for attenuation of the baroclinic semidiurnal tide northward of the Hawaiian Ridge.

- Question: How does PSI work, exactly? Shouldn't be too difficult to find this in a textbook or paper.
- Method: Again, rotary spectral analysis seems essential. I need to get back to coding this weekend and finish that.
- Reading: Kunze, E., L. Rosenfield, G. Carter, and M. C. Gregg (2002), Internal waves in Monterey Submarine Canyon, J. Phys. Oceanogr., 32, 1890– 1913.

Gilmour, A. (1987). A preliminary rotary spectral analysis of inertial currents... New Zealand Journal of Marine and Freshwater Research, 21, 353–357. https://doi.org/10.1080/00288330.1987.9516231

- Summary: The benefits and limitations of rotary analysis are discussed and demonstrated in a case off of the coast of New Zealand, where a rotary analysis indicates the notable presence of intertial frequencies, to be studied further.
- Importance: Provides a good example of the pros and cons of rotary analysis, and a practical application with results. This paper is beneficial for anyone doubting the efficacy of rotary analysis.
- Questions: I still struggle with the actual *how* of performing a rotary spectral analysis. I'm certainly close, but it would be nice if one of these papers actually gave a few equations that they used.
- Useful methods: Rotary spectral analysis, in process.
- Personal opinion: A good paper for understanding the theory of rotary spectra, but a bit short, and somewhat qualitative.
- Additional reading: Gonella (1979)

Gonella, J. (1972). A rotary-component method for analysing meteorological and oceanographic vector time series (Vol. 19). Pergamon Press.

- Summary: Gonella describes a method for calculation the counter-rotating components of a velocity vector, and shows an example of applying this theory to resolving Ekman spiralling, among other derivations of coherence, orientation, etc.
- Importance: A critical work in defining the use of rotary spectral analysis, and providing an example of its application.
- Questions: A bit difficult to follow the notation, which is where I believe I'm making a mistake.
- Useful methods: Rotary spectral analysis, in process.
- Personal opinion: A very good chapter on spectral analysis, but the notation is confusing.
- Additional reading: Lamb, Hydrodynamics (textbook). Check for rotary information.

Thomson, R. E. (2014). Data analysis methods in physical oceanography (Third). Oxford, UK: Elsevier.

- Summary: Derivation of the rotary spectral components, autocorrelation, etc. as they pertain to an analysis of velocity data for physical oceanography.
- Importance: Rotary spectral analysis provides insight into the presence of horizontal circulation, and can reduce the effects of inertial rotation when creating power spectra, to better highlight tidal constituents.
- Questions: Once again, the notation is difficult to follow, and I'm wondering why it changes between every source that deals with rotary spectral analysis.
- Useful methods: Rotary spectra.
- Personal opinion: Well done, and the most clear of all of the sources regarding this type of analysis. Still confuses me a bit, however.
- Additional reading: None from this chapter, as I believe I finally have the rotary spectra working correctly.

Gregg, M. C., & Kunze, E. (1991). Shear and strain in Santa Monica Basin. Journal of Geophysical Research, 96(C9), 16709. https://doi.org/10.1029/91jc01385

- Summary: Acoustic and CTD data were collected over two days in 1989 at Santa Monica basin, for an analysis of internal wave activity to show that shear and strain are intensified as compared to the open ocean GM76 models, contributing to enhanced diffusivity.

- Importance: Confirmed contemporary assumptions that enhanced internal wave activity in coastal waters is related to higher than expected diffusivity, and provides an excellent resource for GM spectra comparisons and parameters.
- Questions: There are many, but I will limit it to: what is the benefit of plotting wavenumber instead of frequency in Hz (frequency seems much more intuitive, to me)?
- Useful methods: Everything in this paper seems useful, particularly the GM appendix. I will refer back to it, regularly.
- Personal opinion: Excellent. Overly comprehensive in their analysis, but that isn't a bad thing.
- Additional reading: D'Asaro 1984, Wind forced internal waves... Hickey 1989, Variability in two deep... G&M 1975, Space-times scales of internal waves... Cairns & Williams 1976, Internal wave observations...

Hamann, M. M., & Alford, M. H. (2020). Turbulence driven by reflected internal tides in a supercritical submarine canyon in: Journal of Physical Oceanography - Ahead of print. Retrieved December 14, 2020, from Journal of Physical Oceanography website: https://journals-ametsoc-org.ezproxy.library.uvic.ca/view/journals/phoc/aop/JPO-D-20-0123.1/JPO-D-20-0123.1.xml?rskey=wr7skm&result=1&tab_body=pdf

- Summary: An analysis of incident mode-1 semidiurnal tides in La Jolla Canyon System shows that reflection and scattering by the supercritical canyon walls (and up-canyon axis)can lead to higher mode waves that can cause elevated mid-depth dissipation, in addition to the near-bottom elevated turbulent dissipation that is expected.
- Importance: Suggests a new process in canyon regions that could contribute to mixing and internal wave dissipation in ways that weren't previously considered.
- Questions: Are there specific criteria for distinguishing between slope canyons and shelf canyons, or is it a qualitative judgement call?
- Useful methods: Tidal filtering and a comparison of wavelength to canyon length, shape, and the criticality of the slope of the canyon walls and axis along its length.
- Personal opinion: Alford's papers are always very clear, and the analysis process explained in just the right amount of detail. This will be very useful for my own tidal analysis.
- Additional reading: Hotchkiss and Wunsch 1982, internal waves in canyons